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7.1. РЕЗОНАНСНЫЕ ПРЕОБРАЗОВАТЕЛИ В БЕСКОНТАКТНОЙ ПЕРЕДАЧЕ ЭНЕРГИИ: ЭЛЕКТРОМОБИЛЬ И ВОЗОБНОВЛЯЕМАЯ ЭНЕРГИЯ

RESONANT POWER CONVERTERS IN CONTACTLESS ENERGY TRANSFER: ELECTRIC VEHICLE AND RENEWABLE ENERGY PROCESSING

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Абстракт: Резонансные преобразователи стали популярны в начале 80-х а позже ими пренебрегали. Их достижения вспомнены сейчас, когда оказалось, что они незаменимы для беспроводной передачи энергии. Резонанс широко употребляется в радиосообщениях, но его новейшая цель, быть инструментом силовой электроники высокого КПД. В этой статье показаны базисные принципы, помогающие приложить идей зарядки батареи электрических/гибридных автомобилей, как в стационарном, так и в динамическом беспроводном режиме. Представлены и другие идеи, напр., замена постоянных магнитов (синхронных) ветреных генераторов. Идеализированный Резонансный Преобразователь Мощности использован для определения режимов с высшим КПД, также для трансформатора с слабой магнитной связью. Предлагается незамедленное управление резонансного преобразователя (с прогнозированием).
Abstract: The resonant converters became popular in the early 1980s, and were quite overlooked later on. Their achievements are remembered recently, when they turned to be irreplaceable for the wireless transfer of energy. The resonance is widely used in the radio-communications but its recent target is to be a high efficiency instrument for the power electronics. In this article, some basic principles are shown that help to implement the ideas of electric/hybrid cars battery charging at distance, both in static and in dynamic (on-line) mode. Other ideas are presented too, e.g. permanent magnets substitution for the (synchronous) wind generators. The idealized Resonant Power Converter is used to define the most efficient modes of operation, also for loosely coupled transformer. An instantaneous (predictive) control of the converter, is suggested.

INTRODUCTION

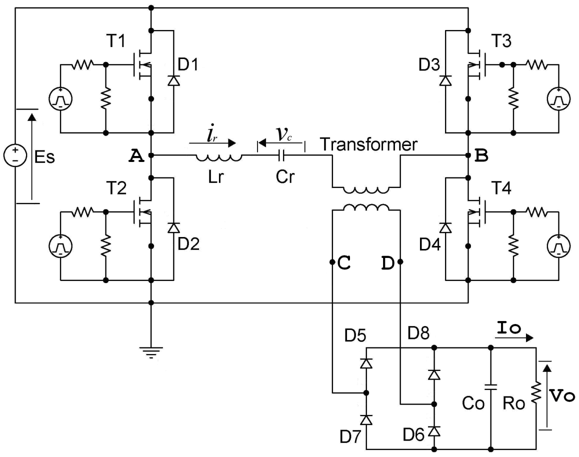
More than a century ago, Nikola Tesla proposed and experimented the (electro-) magnetic resonance as a means for wireless transfer of energy and information. In the communications area the efficiency was and still is not so important, because the most important is the fidelity of the data transfer while the efficiency can go down to, or lower than 0.00001%. Nikola Tesla was the first to consider the energy efficiency at the transmission of high levels of energy. The improvement of the electric/hybrid car battery charging is an urgent need and the knowledge about the resonant contactless transfer became very important. The same is happening with the permanent magnets (PM) machines. Due to the elevated prices of the PMs, the study of the resonant converter demonstrate its suitability for the PM substitution through a contactless energy transfer. There are other possible resonant configurations too.

The Series Loaded Series Resonant (SLSR) thyristor converters appeared in the late 60-s and early 70-s in the works of F. Schwarz and other authors. Later the Zero Voltage Switching (ZVS) characteristics, made it popular in the early 90-s, and recently it reappeared because of the growing necessity for contactless power transfer applications. The operation of SLSR power converter is analyzed in many articles, e.g. in [1] and [2], but to obtain a rapid reaction of this circuit, without exceeding or not reaching the dangerous values of the internal variables, remains a problem. The existence of stored energy in the resonant reactance elements (inductance and capacitance) makes the direct control of the power switches difficult, especially when the circuit elements are not ideal (contactless energy transfer).

SERIES RESONANT CONVERTER

An idealized power circuit of the ideal SLSR converter is presented in Fig.1(a). One of the possible modes of operation is to close alternatively the pairs of switches T_1 / T_2 (and, T_3 / T_4) at a switching frequency above the resonant frequency, i.e. in a super-resonant mode. Other techniques of switching are possible as well, but in general, the circuit of Fig.1a represents the most important idea: it guarantees a Zero Voltage Switching (ZVS).

a.



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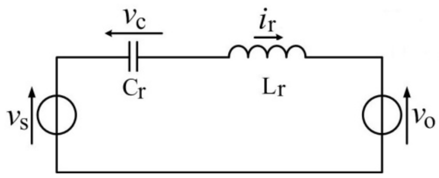

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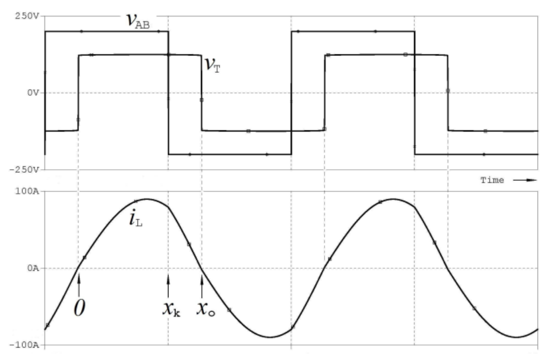

Fig.1. Basic circuit of ideal resonant power converter: a) basic power circuit; b) equivalent circuit of the SLSR power converter; c) state variables waveforms.

The main ideas of calculation in case of the idealized converters are based on the expressions first published in [1], defining the first and the second intervals of 1c:

$$\cos(x_k - 0) = \cos(\psi_f) = \frac{V_{LC2}\left[V_{LC1} + v_c(0)\right] + V_{LC1}\left[v_c(0) - V_{LC1}\right]}{\left[V_{LC1} - V_{LC2}\right]\left[v_c(0) - V_{LC1}\right]} \quad (1)$$

$$\cos(x_o - x_k) = \cos(\psi_r) = \frac{V_{LC1}\left[V_{LC2} - v_c(0)\right] - V_{LC2}\left[v_c(0) + V_{LC2}\right]}{\left[V_{LC1} - V_{LC2}\right]\left[v_c(0) + V_{LC2}\right]} \quad (2)$$

The two formulas are simplified as the excitation voltages are known in the idealized case, being:

V_{LC1}=abs(v_s)-abs(v_o)>0 (3)

V_{LC2}=-abs(v_s)-abs(v_o)<0 (4)

Designating the relation between the rectified output voltage and the supplied voltage by q:

$$\psi_f = \arccos\left(\frac{1 - q - qv_{C\max}}{1 - q + v_{C\max}}\right) \quad (5)$$

$$\psi_r = \arccos\left(\frac{1 + q + qv_{C\max}}{1 + q + v_{C\max}}\right) \quad (6)$$

If the efficiency is considered, then the waveform of the resonant current is important:

$$\eta^{-1} = 1 + \frac{(I_{rms})^2 R_{loss}}{(I_O)^2 R_O} = 1 + (\rho_i)^2 \frac{R_{loss}}{R_O}, \quad (7)$$

$$where: \rho_i = \frac{I_{rms}}{\left|i_r\right|_{AVG}} \quad (8)$$

The best zone of operation for this converter is in the top left corner of the diagram in Fig.2:

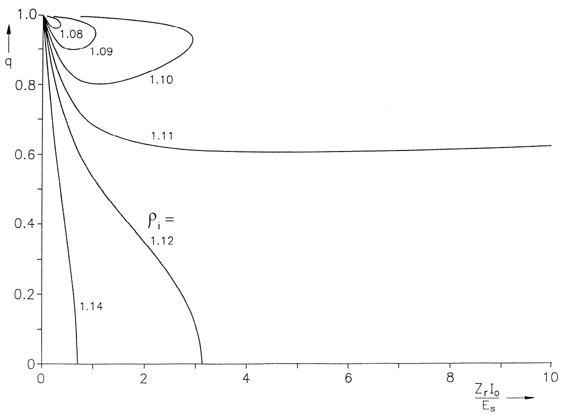

Fig.2. Output characteristics with the zones of best efficiency

LOOSELY COUPLED RESONANT CONVERTER

The ideal (with a good magnetic coupling) resonant power converter is further used as a building block in the more difficult for direct calculation, contactless power converter. The example of a transformer, in the contactless transfer version is shown in Fig. 3.

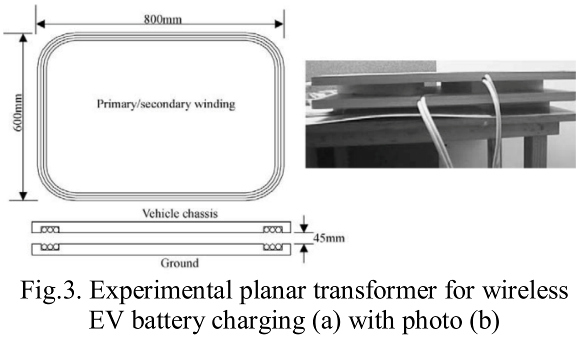

Fig.3. Experimental planar transformer for wireless EV battery charging (a) with photo (b)

As it is seen in Fig.3 the air gap of this transformer is large and even when ferrite plates are used, the magnetic coupling is very weak. The ideal case formulas from [1] and [2] are recalculated to represent this more complicated contactless case [10].

The simplified calculation consists in separating the primary from the secondary sides of the transformer and recalculating two depending on each other differential equation groups. The necessary parameters are then recalculated separately for each side. In most cases, this recalculation works sufficiently well and permits to operate observing mainly the primary side of the transformer.

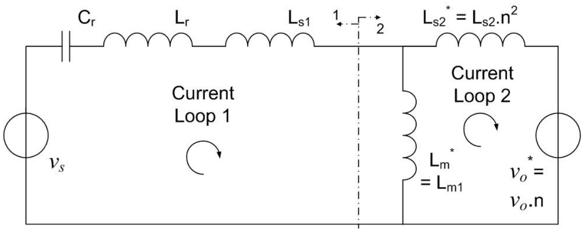

Fig.4. Idealized primary loop of the loosely coupled resonant converter.

With similarly recalculated secondary (the primary is the most important for the control) the recalculated parameters are used in simple equivalent circuits, identical to the presented in Fig.1b.

SIMPLE INSTANTANEOUS CONTROL

The methods to control the power converters can be different but usually the Continuous Current Mode (CCM) operation is preferred at the highest output power levels: that is periodically alternatively closing of switches in pairs (T_1 and T_4) or (T_2 and T_3). The regulation is made through the switching frequency variation, i.e. “frequency mode” (FM). It is proved in [1] that the average rectified current depends on the switching interval Tsw/2 = ($\psi_f + \psi_r$) = ($\psi_1 + \psi_2$):

$$I_o = \frac{2v_{c\max}}{\frac{T_{SW}}{2}} = 4\left(\frac{v_{c\max}}{T_{SW}}\right) \tag{9}$$

A simple PLL circuit, regulating the phase shift between the two diagonals switching, could set the regulation:

$$I_0^N = \frac{Z_r I_o}{E_s} = \frac{2\dfrac{(1+q)(1-\cos\psi_2)}{\cos\psi_2 - q}}{\psi_2 + \arccos\left(\dfrac{1-q-q\dfrac{(1+q)(1-\cos\psi_2)}{\cos\psi_2 - q}}{1-q+\dfrac{(1+q)(1-\cos\psi_2)}{\cos\psi_2 - q}}\right)} \tag{10}$$

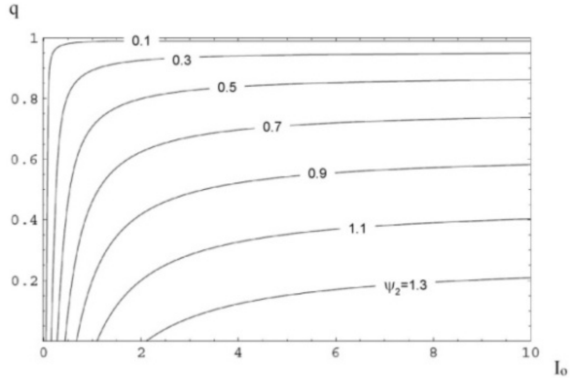

Fig.5. Normalized output voltage q in function of normalized output current, regulated by angle ψ_2

The regulation is especially good in case of falling load characteristics (discharge, laser, etc.) but for the normally required voltage stabilization, the reaction will be too slow (heavy filtering).

It is more efficient to apply a switching frequency higher than the resonant frequency (super-resonant operation), making it the lowest when the highest power is required. By keeping the switching frequency higher than the resonance, the zero voltage switching (ZVS) of the power devices is guaranteed [1].

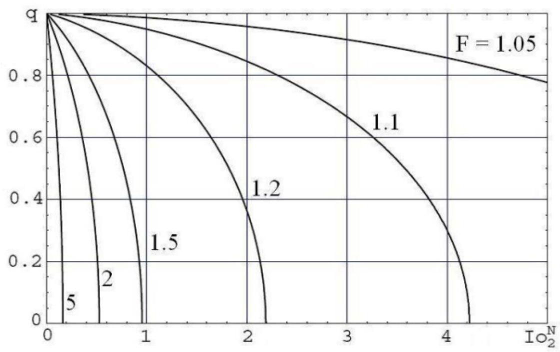

Fig.6. Output characteristics at different normalized switching frequency F

As the range of regulation obtained by frequency variation is relatively narrow, as shown in Fig.6, it is combined with the less efficient pulse-width mode (PWM) of switching, as e.g. in [2], to achieve a deeper regulation of the output power (Fig.7). The PWM regulation is limited at the relative frequency F = 1.5, where the resonant capacitor will never discharge in reverse direction, provoking a short circuit like in the thyristor inverters in the fixed frequency mode of operation [2]. In [2] a useful limit is defined (seen in Fig.7) that guarantees the minimum of switching losses and minimum risk of instability, i.e. PWM must be allowed only when the resonant capacitor voltage amplitude is lower than the supply voltage (or 1+q). This restriction is sufficient even for the contactless energy transfer.

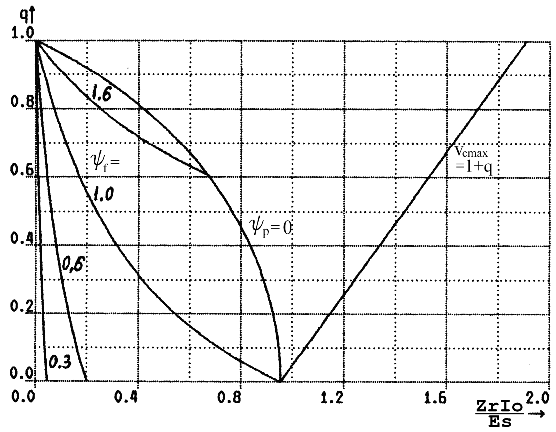

Fig.7. Output characteristics q=f(I_o) for PWM at F=1.5, regulated by interval ψ_f

At the zero crossing points of the resonant current (Fig.1c) the total resonant tank energy consists only of energy accumulated in the resonant capacitor, i.e. $½C_r v_{cmax}^2$, so the maximum capacitor voltage v_{cmax} can be used to assess that energy [1]. Integrating the energy balance in half-periods, results in:

$$\Delta \mathscr{E}_{LC}=V_{LC1}[v_c(t_1)-v_c(0)]C_r+V_{LC2}[v_c(½T_{sw})-v_c(t_1)]C_r \quad (11)$$

The excitation voltage V_{LC} can be rewritten in its normalized forms [1]: V_{LC1}=1-q and V_{LC2}= -1-q. The normalized output voltage q is supposed to be constant during one switching period. Then the change of the resonant capacitor energy (in normalized form) is:

$$\Delta \mathscr{E}_{LC}^N = \Delta \mathscr{E}_C^N(0,½T_{SW}) = 2v_c(t_1) - q(v_{c\max 1} + v_{c\max 2}) \quad (12)$$

This expression includes the capacitor voltage $v_c(t_1)$ at which the conducting semiconductor switches are turned off. The equation involves also the previously measured amplitude v_{cmax1} and the desirable next amplitude v_{cmax2} which may be different if it would be required to change the value of the next transmitted energy portion. During an increase of the output power the energy portions must rise and during a reduction of the output power the energy portions will need to decrease.

In the case of contactless power transfer, the converter operation is described by the modified expressions where v_{cmax1} and v_{cmax2} correspond to the resonant capacitor voltage amplitudes in the primary side of the transformer [13], substituting the normalized output voltage q by the corrected value q^T=Kq, where K is the magnetic coupling factor of the loosely coupled magnetic link.

The SLSR converter may keep its steady-state operation during long time if there is no necessity to vary the load and the input power parameters stay stable. In that case, the initial resonant capacitor voltage and its final value (v_{cmax1} and v_{cmax2}) are identical and opposite by polarity. Then the transistors must switch off when this voltage is reached:

$$v_c(t_1) = qv_{c\max} \quad (13)$$

In Fig.8 it is illustrated the turn-off of the transistors, defined by the previous amplitude v_{cmax1} and the desired next amplitude of the capacitor voltage v_{cmax2}.

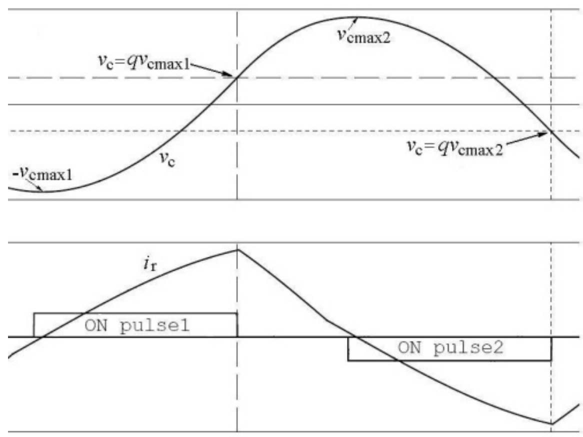

Fig.8. Switching off of the resonant current

The plots in Fig.8 illustrate the steady-state equation (13). To keep the amplitudes of the resonant capacitor voltage v_{cmax} unchanged, it is necessary to keep the switching off at its level defined by (13). The regulation method will require a calculation by multiplying the normalized output voltage q and the last measured amplitude voltage of the resonant capacitor.

The requirement for a positive increment $\Delta \mathscr{E}_{LC}$ of the energy portions corresponds to a higher consumption of power at the output. The control action is to produce the turn-off of the transistor (or diagonal) at a certain level $v_c(t_1)_{new}$ that will be higher (added normalized energy $\Delta \mathscr{E}_{LC}^N$) than the steady state value $qv_{c\max 1}$:

$$v_c(t_1)_{new} = qv_{c\max 1} + \Delta \mathscr{E}_{LC}^N = qv_{c\max 2} \quad (14)$$

The expression (14) is simplified in order to suit better the practical implementations. The (normalized) energy increment $\Delta \mathscr{E}_{LC}^N$ is expressed in (15) as a voltage increment Δv_{cmax1}. A more exhaustive evaluation of the energy portions is not necessary:

$$v_c(t_1)_{new} = qv_{c\max 1} + q\Delta v_{c\max 1} = q(v_{c\max 1} + \Delta v_{c\max 1}) \quad (15)$$

In a steady state operation the simulation results can be seen in Fig.9. The output voltage has a considerable ripple (by purpose), applying a reasonably low capacitance of the output filter, thus guaranteeing to show clearly the faster reaction of this method for controlling the resonant converter.

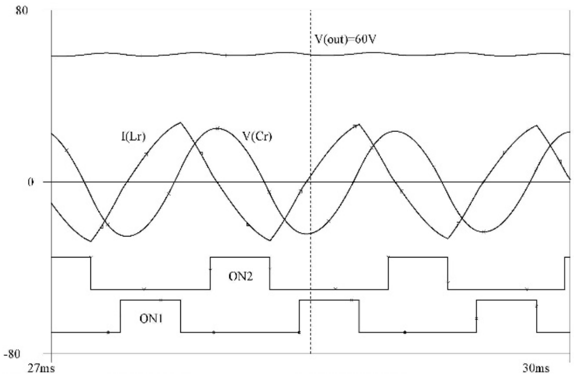

Fig.9. Steady state operation.

The fast increase of the output voltage is presented in the state variable diagram shown in Fig.10. Only a few current amplitudes are necessary to reach the required steady-state operation.

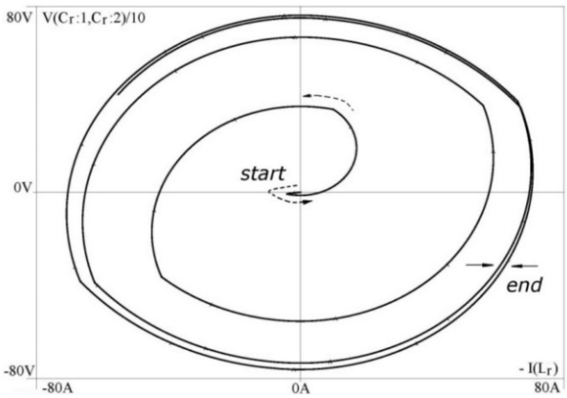

Fig.10. State variable diagram (v_c and i_r).

Fig.10 shows the good response of the circuit to the output requirements. The reference signal was increased from zero to a signal corresponding to higher output voltage.

ELECTRIC VEHICLE BATTERY CHARGING

The most problematic building block of any autonomous electric driven vehicle (including robots) is and will be its electric energy source, i.e. the BATTERY. The battery delimits the most important characteristics of the vehicle: the total available energy (i.e. its autonomy) together with the achievable velocity and acceleration (i.e. maximum instantaneous power, both for propulsion and for braking).
For example, the Li-Ion battery of 25 kWh can guarantee 160 km of autonomy (Nissan-Renault) but its weight is more than 150 kg and costs at least 12000 Euros. In parallel, a fuel tank of 50 litters will be sufficient for 900 or more km autonomy. The electric motor has advantages, but they are not sufficient to compensate for the battery disadvantages: heavy, expensive, short life, etc. Of course, the technology of batteries is developing but it will be always necessary to consider their characteristics in order to make more efficient the energy storage. For example, the lack of suitable batteries is the reason for the HEV and Plug-in HEV to exist. In case of HEV and especially PHEV the battery is smaller and the speed (the power) of charging is usually limited to the household grid capacity. It is not easy to decide if fast or slow charging will be adopted. The internal combustion engine habits are strongly influencing the thinking of the consumer but it is predictable that a slower and more regular charging will be more efficient (lower power required, longer battery life, smart grids, etc.). The contactless charging is capable to offer higher power charging solutions both for slow and fast charging, but it is not so attractive to apply megawatt power to succeed in charging for 5 minutes (Fig.11).

Fig.11. Contactless charging (static)

The on-line charging is another solution that will diminish the requirements for a huge battery capacity (Tesla S has 85 kWh battery). It will be sufficient only 6 kWh battery if the dynamic (in movement) charging is applied. An example, it is shown the installed in Daejeon (R of Korea) electric vehicle path where the road is prepared by resonant windings built in the pavement, so the bus can charge its batteries during its run (Fig.12 and Fig.13).

Fig.12. The generator cabinet and the bus road (grey)

Fig.13. The magnetic bottom of the bus (Daejeon, KAIST)

PERMANENT MAGNETS SUBSTITUTION

The situation with the rare earth materials is critical. The price is rising each year, and only few countries own the permanent magnet production material. Here is a possibility for a new, contactless solution: The magnetization of the rotor in the windmill generator is possible through the rotary transformer in Fig.14, through which the magnetization will enter the rotor.

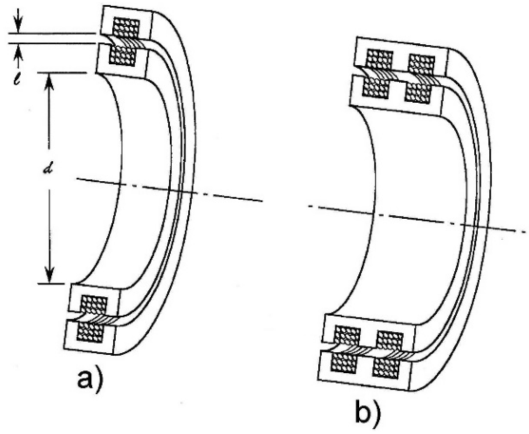

Fig.14. One of the many rotary transformer constructions

CONCLUSION

The contactless energy transfer is still not 100% efficient but it provides new technological solutions and promises a good perspective to the energy saving and to a cleaner world. The instantaneous control brings stability by controlling the resonant capacitor voltage.

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